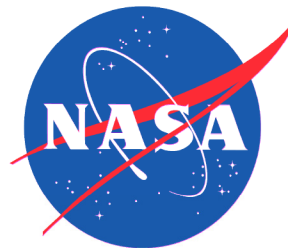


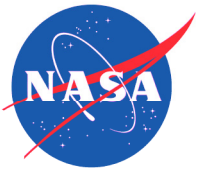
Command and Data Handling System for the Panchromatic Fourier Transform Spectrometer

Dmitriy Bekker, Jean-François Blavier, Dejian Fu, Richard Key, Ken Manatt,
Colin McKinney, David Rider, Stanley Sander, Thomas Werne, Amy Wu, Yen-Hung Wu

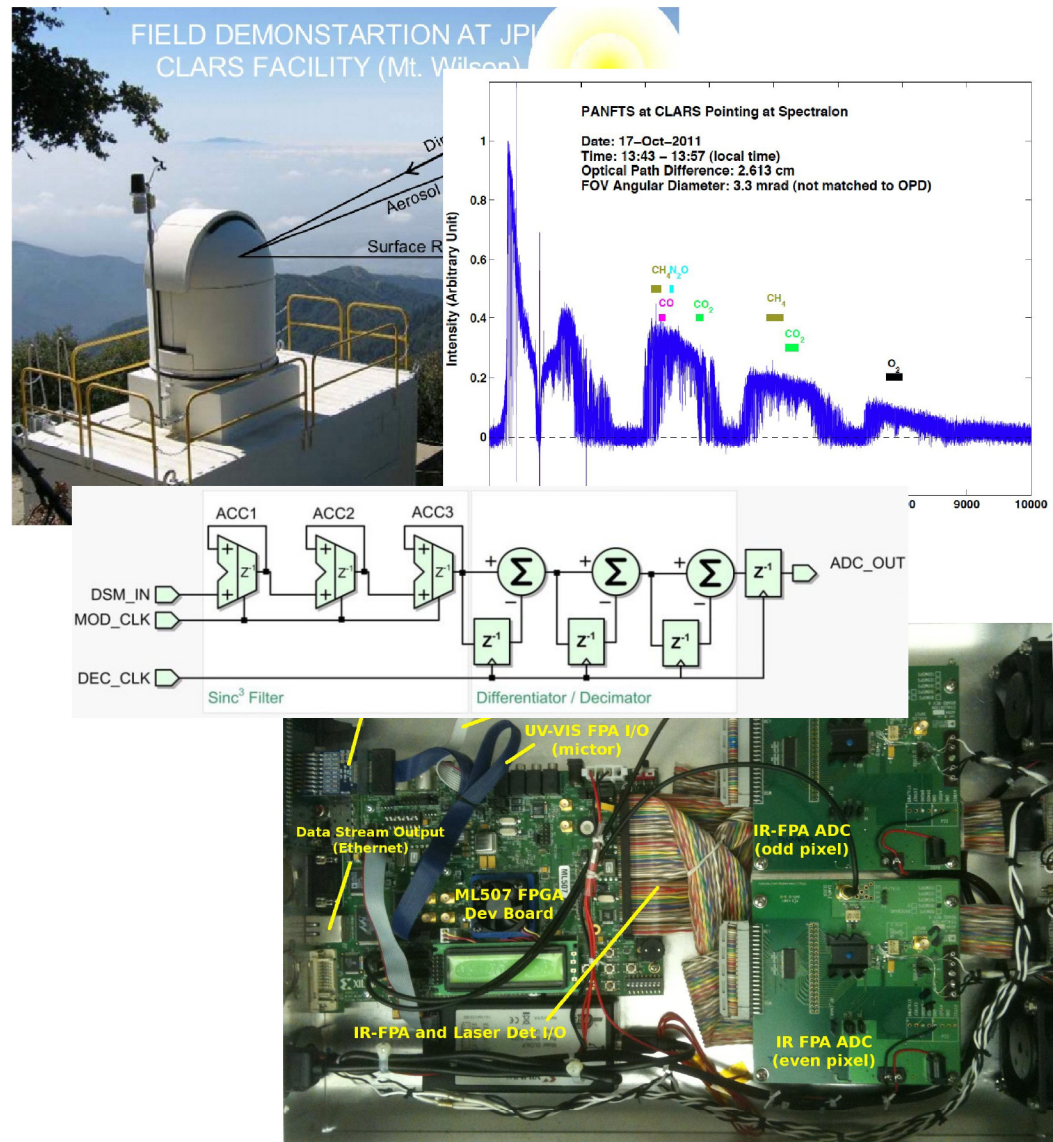
Jet Propulsion Laboratory
California Institute of Technology

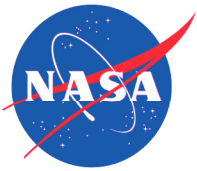


March 4, 2012
IEEE Aerospace Conference
Big Sky, MT



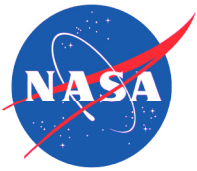
- The PanFTS Instrument
- Breadboard Architecture
- FPA Data Acquisition
- Sigma-Delta Filter Design
- OPDM Control
- Functional Test
- Recorded Spectra
- Current Progress
- Conclusions





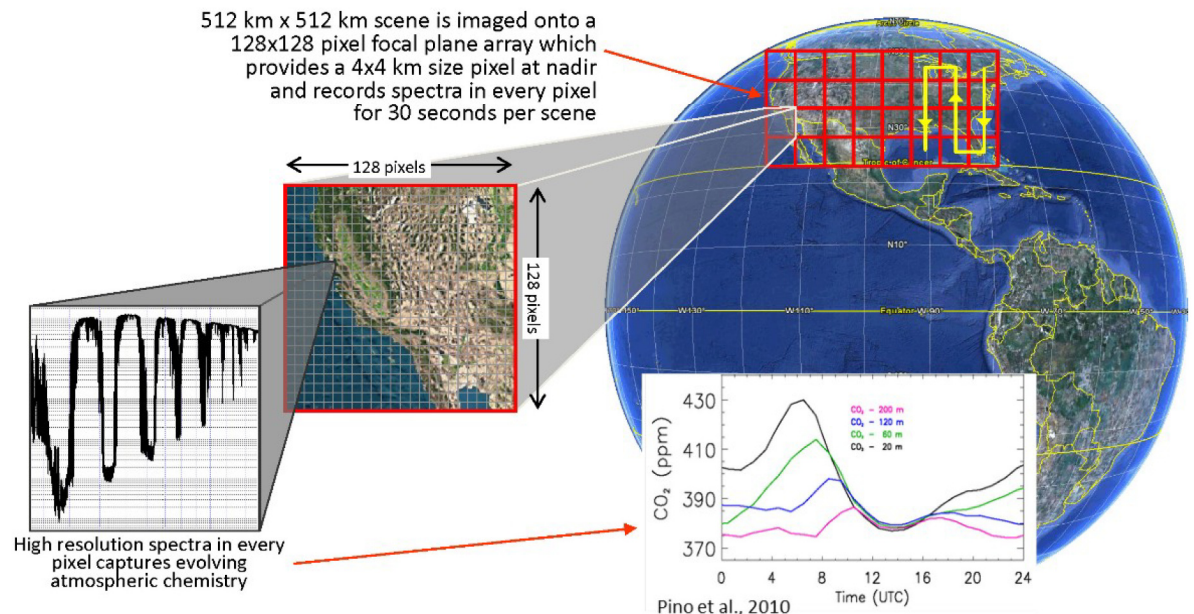
The PanFTS Instrument

- PanFTS is an Imaging Fourier Transform Spectrometer
 - Michelson interferometer (two in parallel)
 - “Camera” instead of traditional detector
 - Pictures recorded at high frame rates; path difference continuously varied
 - Fourier transform of each pixel recorded yields spectrum at observation
- Targeted for the Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission – recommended by NRC Decadal Survey
- Multiple focal plane arrays (FPA) for IR and UV-Vis measurements
 - Goal: 128x128 pixels, 8kHz frame rate
 - Current progress: IR (Raytheon FPA) and UV-Vis (JPL developed), operation at CLARS site on Mt. Wilson, CA.
 - Present capability: trades spatial coverage for frame rate
- FPGA and commercial ADCs control/gather data from FPAs

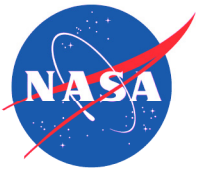


The PanFTS Instrument

- Each of four cameras cover a 512 km square scene at nadir
 - 30 second scan time per scene
 - 16 minute coverage of continental U.S.
- Key technology developments
 - High efficiency optical layout
 - Novel optical path difference mechanism
 - High frame rate FPAs
 - Processing elements to handle huge data rates



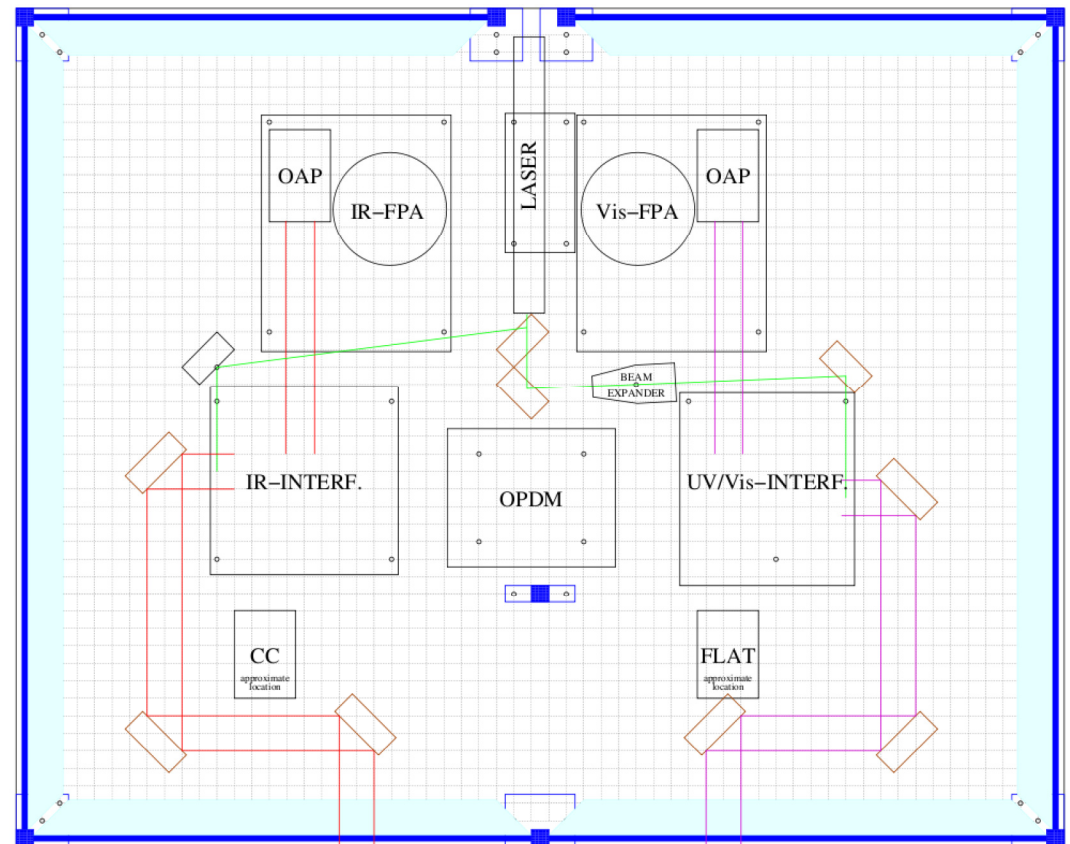
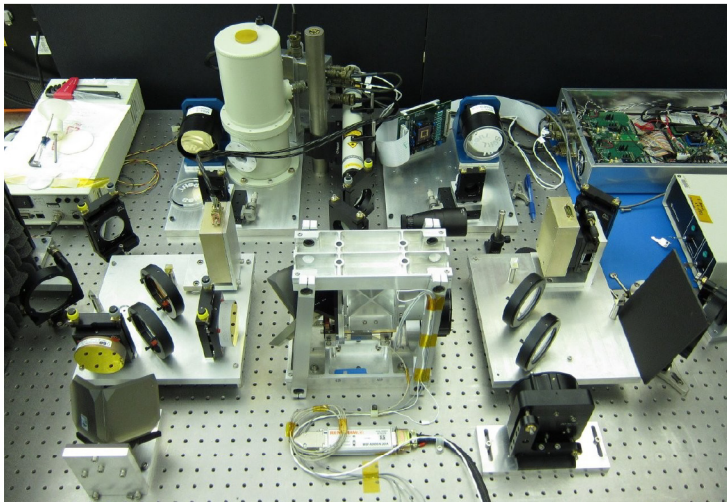
Imaging FTS observation scenario for GEO-CAPE mission



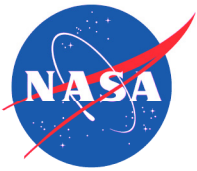
Breadboard Architecture

Optical Layout

- Two parallel interferometers (cover IR and UV-VIS)
 - Shared OPDM
 - Shared metrology laser
- 12-inch focal length off-axis parabolic mirrors

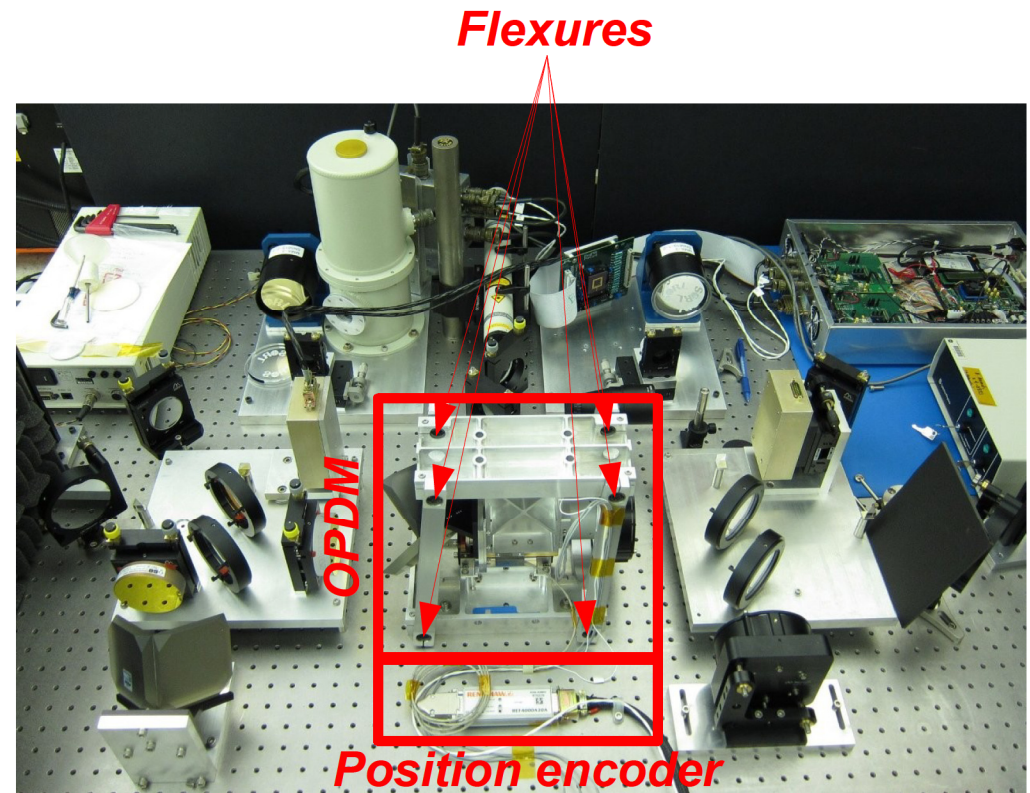


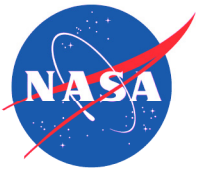
Optical layout of the PanFTS breadboard instrument



Optical Path Difference Mechanism (OPDM)

- Provides precise control of the optical path difference
- Flexure-based parallelogram design
 - Low tip/tilt error
 - “Infinite” life
 - Over 2.5M scans at vacuum and temperature (173K)
- Residual tip/tilt error in UV-VIS interferometer corrected by piezo stage
- Servo system drives voice-coil to control displacement

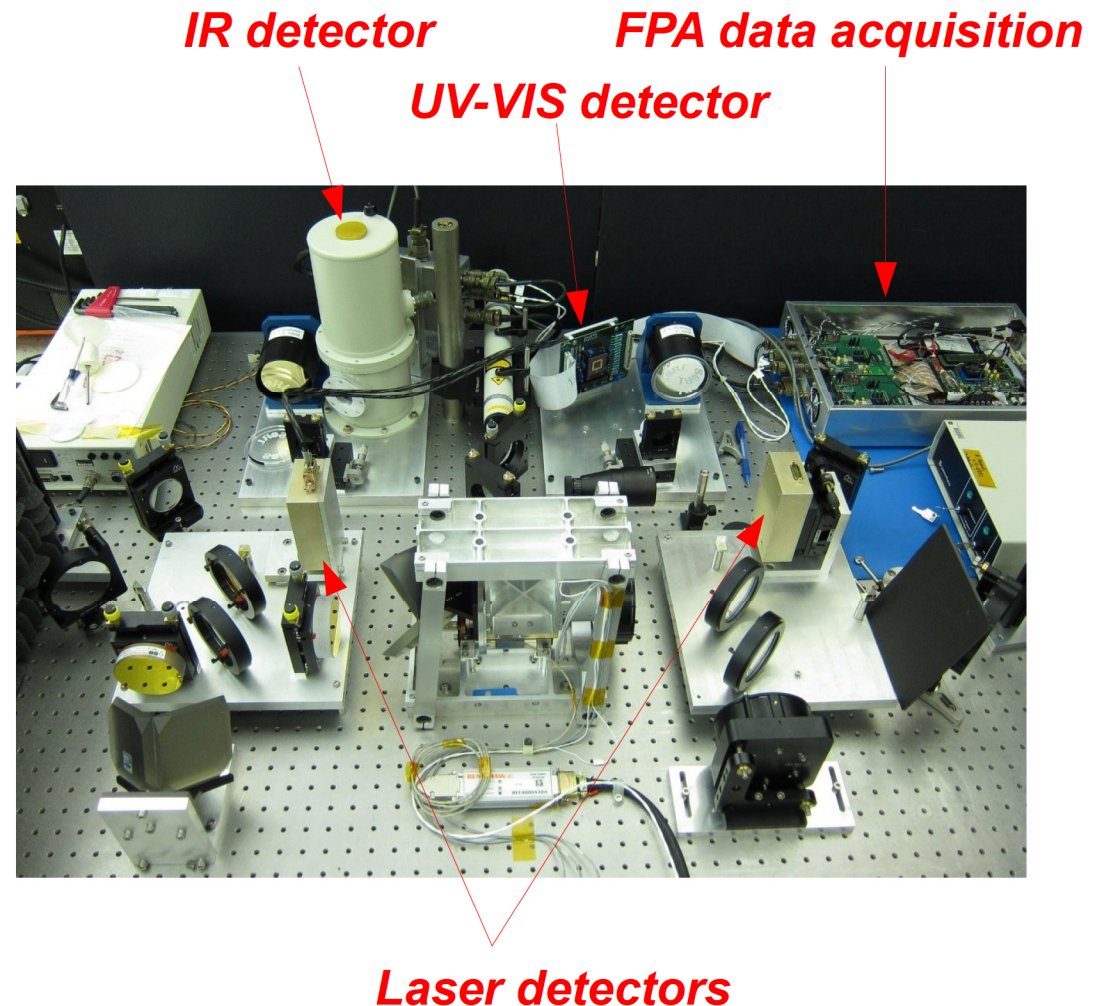


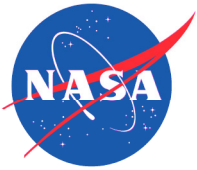


Breadboard Architecture

FPA Signal Chain

- JPL UV-VIS FPA (4x4)
 - First order sigma-delta ADC per pixel
- Raytheon IR FPA (256x256)
 - Windowed to 8x8 pixels
 - Analog output
- FPA data acquisition (FPGA)
 - Filter UV-VIS data
 - Capture IR data (ADCs)
 - Capture laser data
 - Synchronize all streams





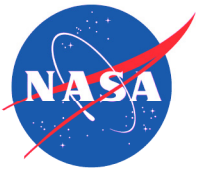
Breadboard Architecture

OPDM Signal Chain

- Command and monitor state of translation mechanism
 - Servo controller board (JPL)
 - FPGA development board
 - Position encoder
- IP developed to:
 - Read OPDM position
 - Control OPDM with PID
 - Drive OPDM voice coil
 - Correct tip-tilt error
 - Monitor voltage, current, temperature

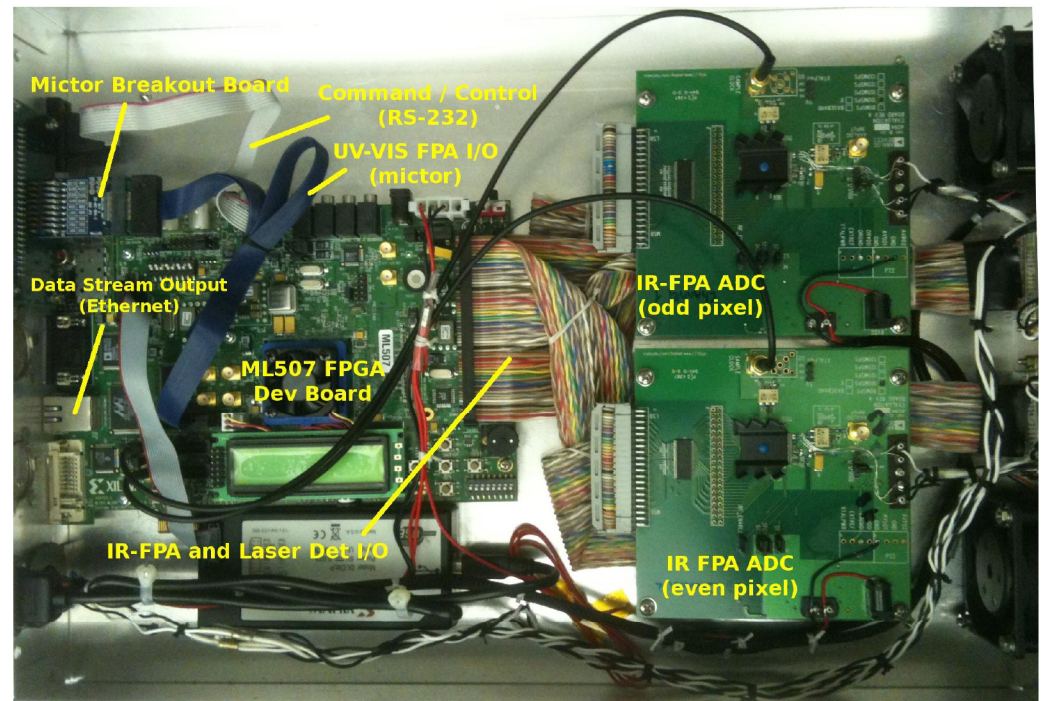
Data Display & Spectra Proc.

- OPDM control and FPA data acquisition communicate with single workstation
 - OPDM control and monitoring via RS232
 - FPA control via RS232
 - FPA data acquisition via Ethernet (TCP/IP)
- Data display via Matlab
- Data analysis via separate suite of programs

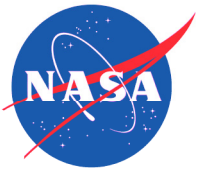


FPA Data Acquisition

- Simultaneous, synchronous capture from IR, UV-VIS, and laser detectors
- Virtex-5 FPGA used to control and collect data
 - UV-VIS FPA (digital)
 - IR FPA(analog) via ADCs
 - Laser (analog) via ADCs
- Sigma-delta filtering on FPGA for each UV-VIS pixel
- Embedded processor (PowerPC) controls data streams
- User commands sent via RS-232
- Data sent to workstation via Ethernet (TCP/IP)



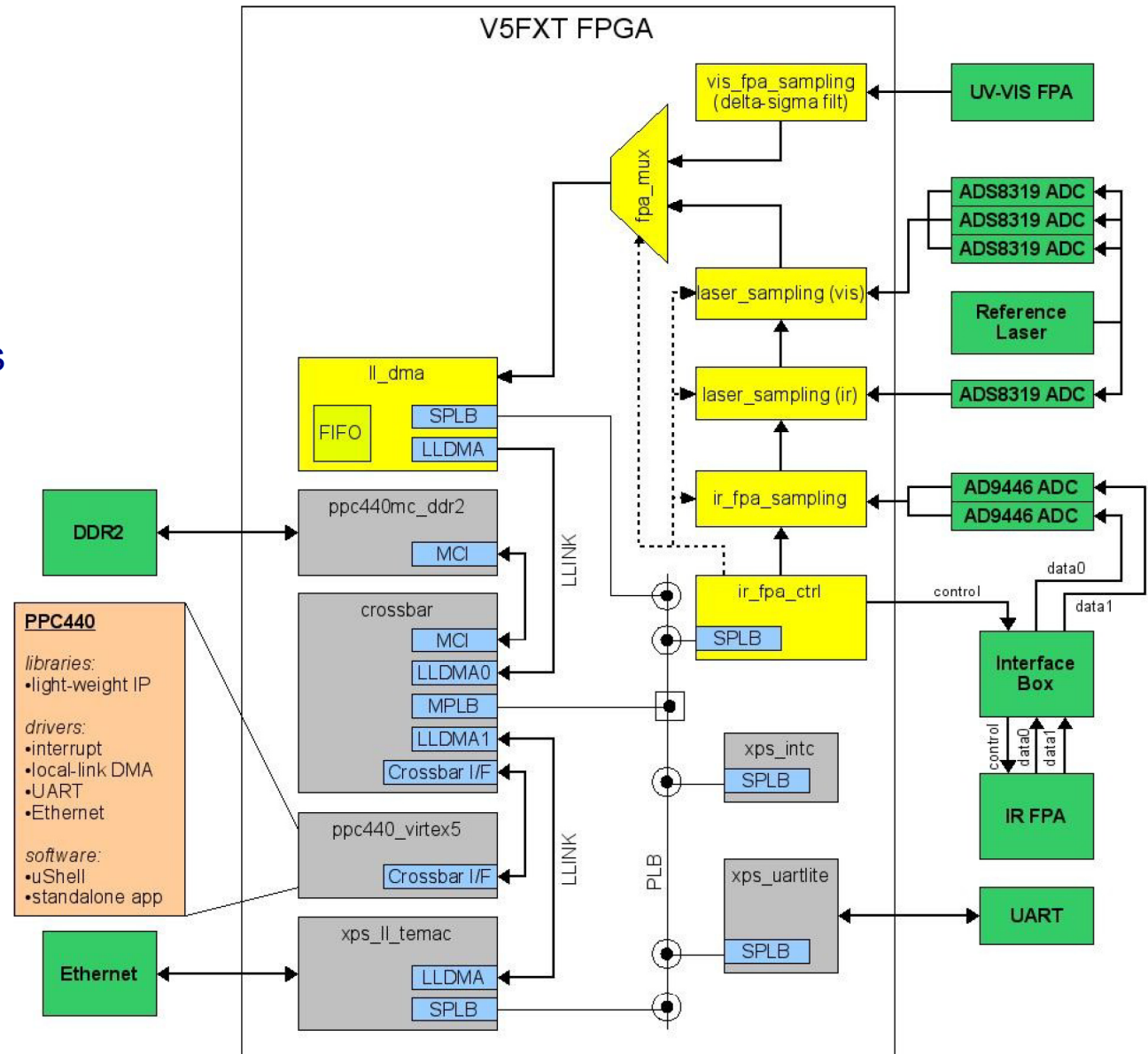
FPA Data Acquisition Electronics

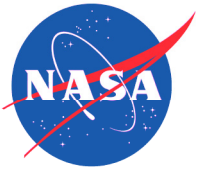


FPA Data Acquisition

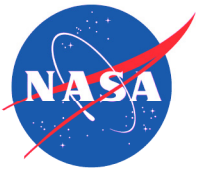
Data
↓
Memory
↓
Ethernet

- *ir_fpa_ctrl* – begins command cycle
- *ir_fpa_sampling* – grabs one frame of data from IR ADCs
- *laser_sampling (ir)* – grabs single channel laser data
- *laser_sampling (vis)* – grabs triple channel laser data
- *fpa_mux* – switches from IR and laser stream to UV_VIS FPA stream and grabs one frame of UV-VIS data
- *vis_fpa_sampling* – runs continuously, sigma-delta filtering UV_VIS data



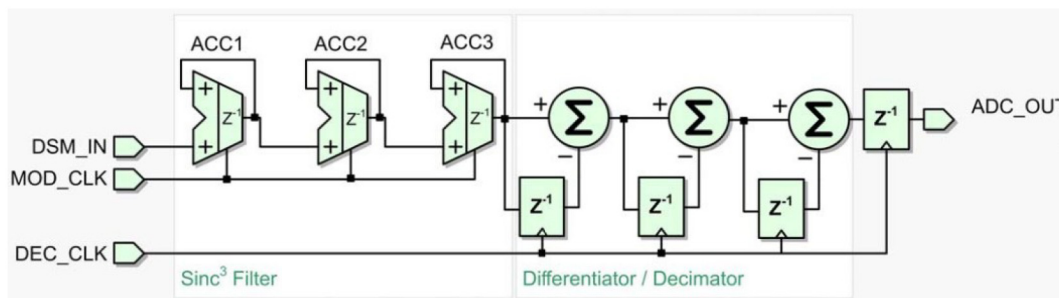


- Embedded processor on FPGA runs a micro shell environment (μ Shell), accepting commands from user via RS-232
- Raytheon IR FPA (256x256) settings
 - Number of rows and columns, for windowing (in multiples of 8)
 - Row / column start coordinates (for windowing)
 - Frame rate, integration time
 - Bias, crosstalk, transimpedance, offset
- CPU check user input parameters are within range (IR FPA)
- Sigma-delta filtering performed in real-time per pixel (UV-VIS FPA)
- Currently, one mode in which all FPAs and laser detectors are simultaneously sampled
 - IR: windowed to 8x8, frame rate = 7.8125 kHz
 - UV-VIS: full array (4x4), sigma-delta filtered output rate = 7.8125 kHz



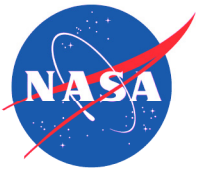
Sigma-Delta Filter Design

- UV-VIS FPA is essentially a sigma-delta converter without the digital filter on chip
- FPA output from modulator, 1-bit stream at 1.953 MHz (per pixel)
 - High sampling rate allows for simple anti-aliasing filter to be implemented on output
 - Pushes noise out to higher frequencies
- Digital filter needed to interpret modulator output with 16 bit resolution
 - 3 stage accumulator (Sinc³) followed by 3 stage differentiator-decimator
 - Replicated 16 times on FPGA (per pixel)
 - Decimation rate set to N=250, to produce 1.953 MHz / 250 = 7.8125 kHz



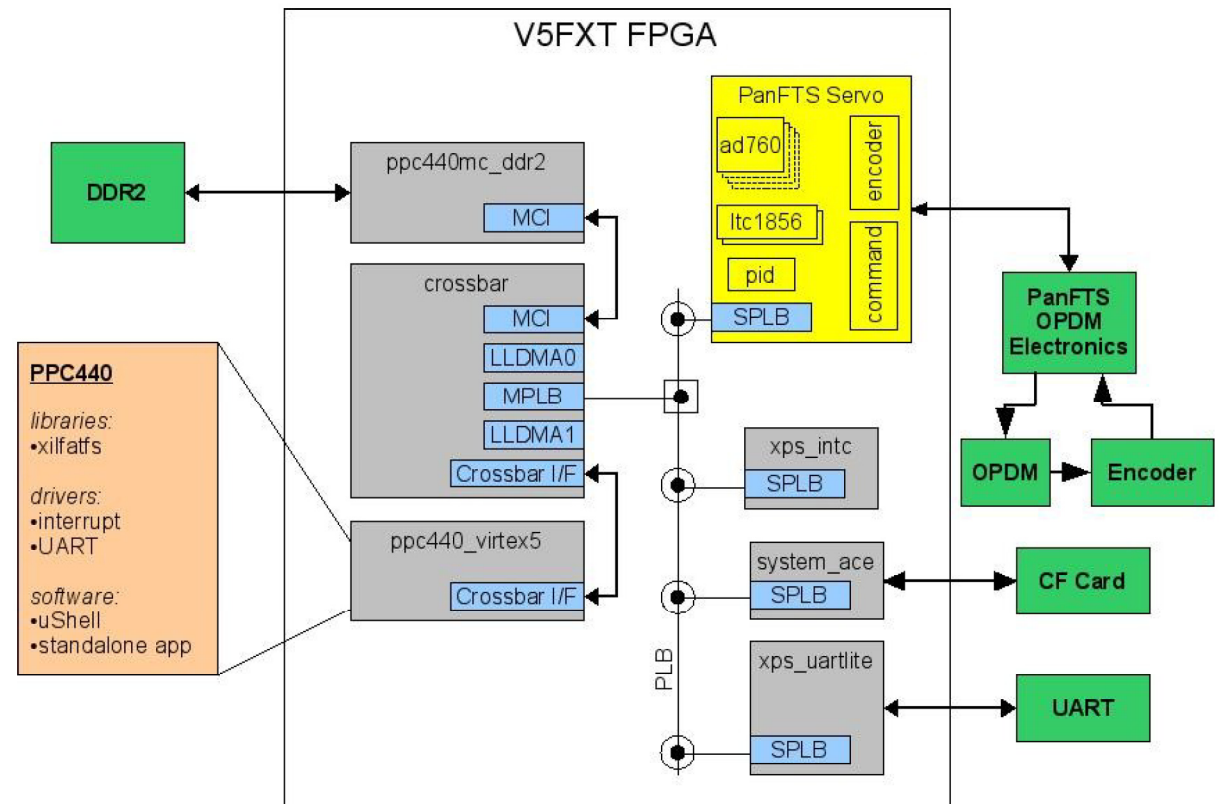
$$D_3(z) = \left(\frac{1 - z^{-N}}{1 - z^{-1}} \right)^3 X(z)$$

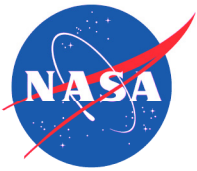
$$D_3(z) = \left(\sum_{i=0}^{N-1} z^{-i} \right)^3 X(z)$$



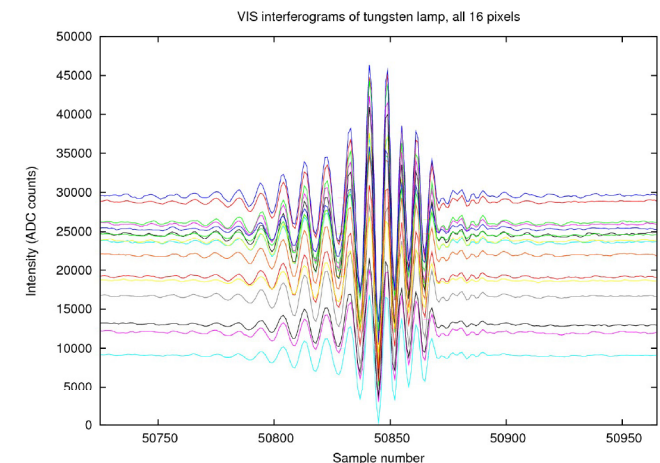
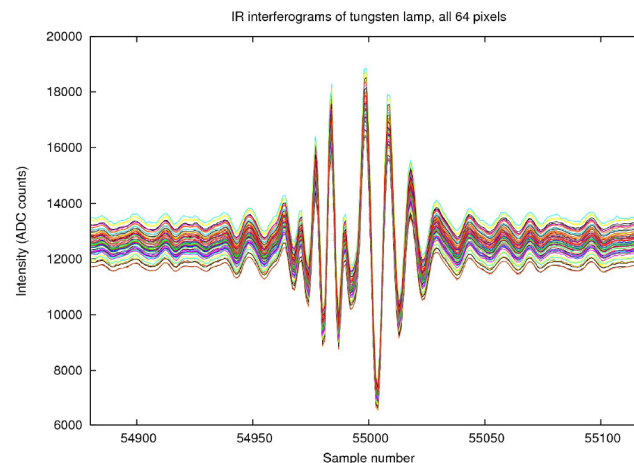
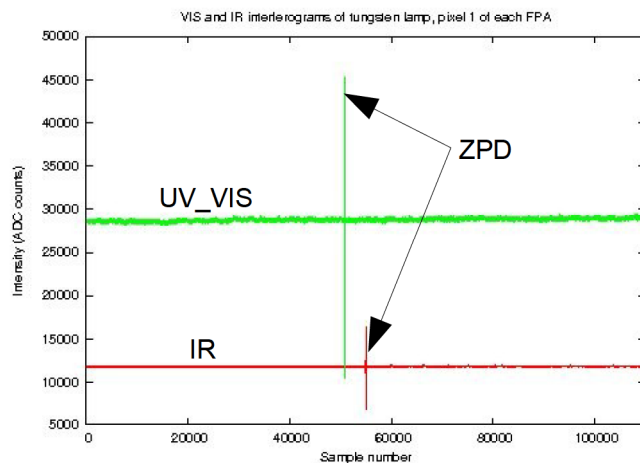
OPDM Control

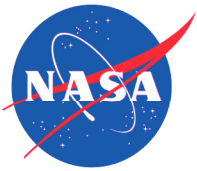
- OPDM controlled by FPGA and servo system electronics (separate system from FPA data acquisition)
- OPDM commanded by standard discrete-time PID controller
 - Control loop calculation performed in FPGA fabric
 - PID parameters alterable from within software environment
- Over-current protection monitors sustained large current draws in voice-coil, sends OPDM into “safe” mode
- FPGA keeps track of cycle count, stored on CF Card (used in lifetime test)



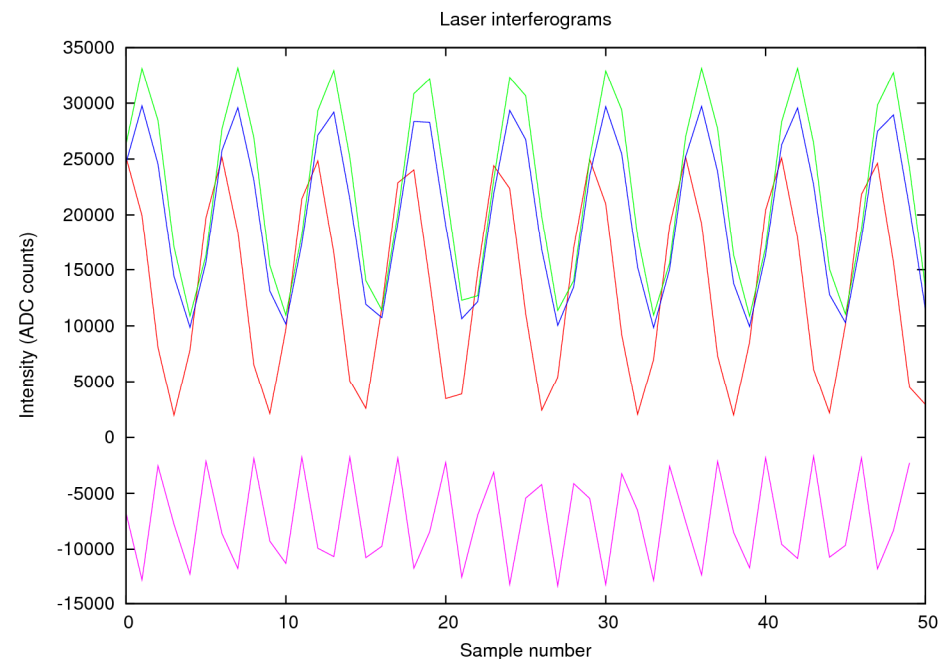


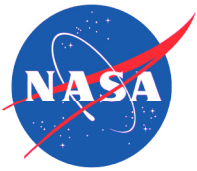
- Laboratory functional test used bright tungsten lamp to illuminate inputs of both interferometers (IR and UV_VIS)
- Spikes near the middle of the traces (see below) caused by constructive interference at zero path difference (ZPD), producing the strongest signal at the detectors
- Displacement in ZPDs due to being created in two separate interferometers
 - Possible to line up ZPD, moving cube corners (IR), flat mirror (UV_VIS)
 - Possible to operate IR interferometer with ZPD near one end of record, increasing spectral resolution in IR domain (advantage of PanFTS design)





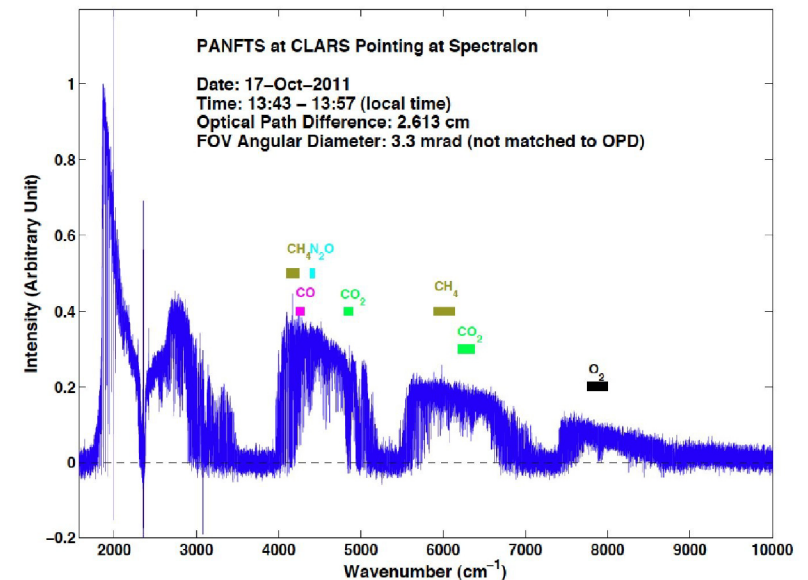
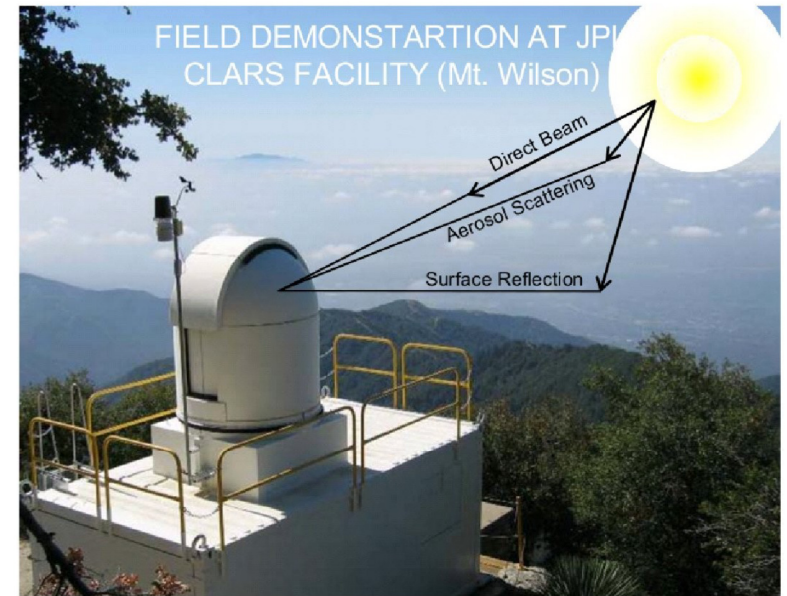
- Laser channels also recorded
 - Triple channel on UV_VIS side (because flat mirror requires tip/tilt correction)
 - Single channel on IR side (no correction needed, using cube-corners)
- Phase measured on UV_VIS channel, compensated by driving piezo actuators in OPDM
- IR laser appears at 2x frequency of UV_VIS, due to double passing of the optics in IR interferometer (shifted down for clarity)
- Laser signals are used to re-sample FPA data (IR and UV_VIS) onto a grid of equidistant optical path difference steps (post-processing)

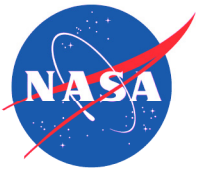




Recorded Spectra

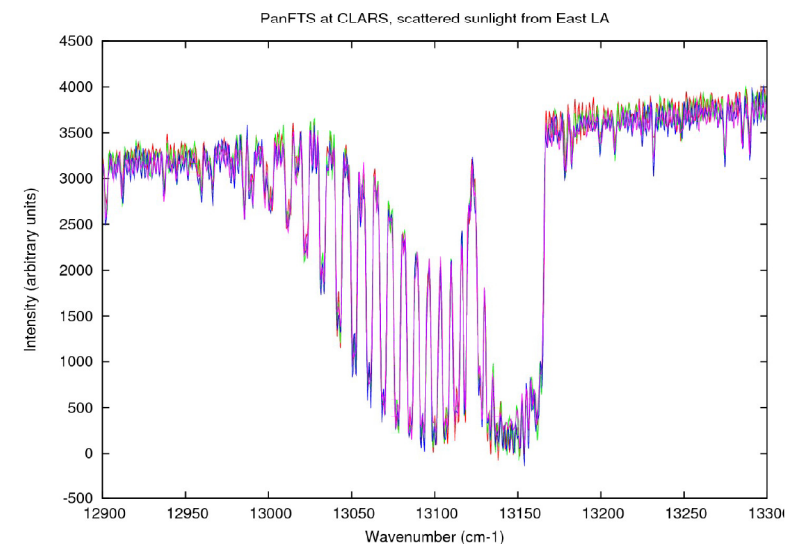
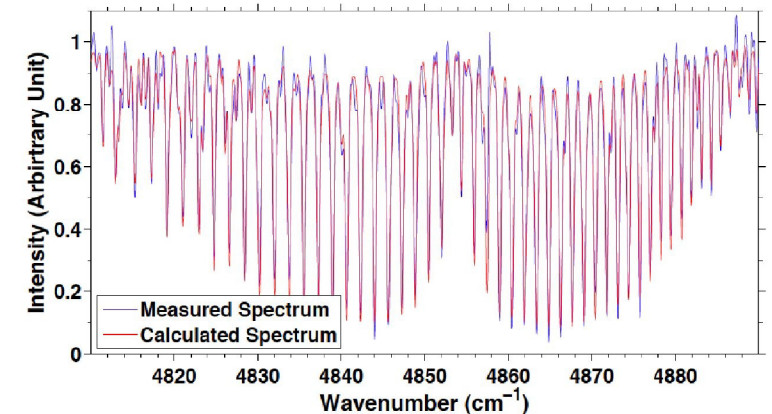
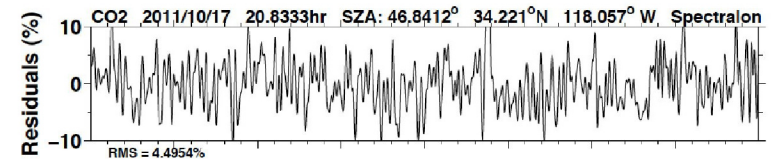
- Instrument moved to CLARS (California Laboratory for Atmospheric Remote Sensing)
- Replaced FPAs with single-element detectors
 - Low light levels produced by scattered sunlight
 - Low SNR on FPAs (debugging)
 - Used InSb for IR, Si for UV_VIS
- Measured absorption features from atmosphere above Mt. Wilson
 - Pointed instrument to Spectralon plate
 - Recorded and processed interferograms

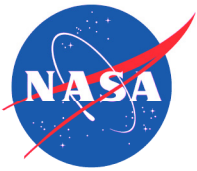




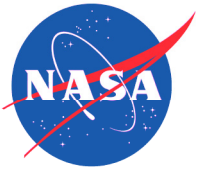
Recorded Spectra

- Comparing recorded spectrum to a computer model confirms FTS is working correctly
 - Section of spectrum at $2.06\text{ }\mu\text{m}$ (at right) showing CO_2 band fitted by a computer program (models atmosphere and instrument line shape) to produce synthetic spectrum
 - Residual between measurement and model dominated by random noise
- Interferometer stability confirmed by comparing four consecutive spectra from the East LA water reservoir
 - Showing spectral region containing $0.76\text{ }\mu\text{m}$ oxygen A-band
 - Consistency is clearly visible

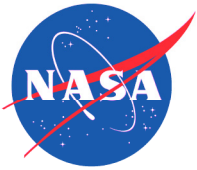




- Main issue is low SNR level from the detectors, FPA data acquisition
- Raytheon IR FPA:
 - Progressively check SNR ratios to see where low SNR is most evident: ADCs, ADCs+preamp, ADCs+preamp+detector
 - Run data acquisition with ADCs at 20x oversampling, then perform averaging
 - Insert glass plate in cold dewar in front of detector to reduce thermal IR pickup from within the instrument
- JPL UV_VIS FPA:
 - Tweak FPA parameters (detector bias, injector charge, etc)
 - Work on using the FPA in an alternate run-time configuration
 - Compare SNR of raw data recording to filtered recording



- In its third and final year of the Instrument Incubator Program, PanFTS breadboard instrument moved to the CLARS facility
 - Able to capture atmospheric spectra of LA basin
 - Development of instrument moves to engineering model phase
- Progress in past year:
 - Addition of UV_VIS FPA to data handling system, with real-time sigma-delta filtering in FPGA
 - Ability to perform simultaneous recordings from IR and UV_VIS FPAs
 - Addition of multi-channel laser detectors to data handling system
 - Improvements in the OPDM and IR FPA configuration setting
- Near-term to-do:
 - Debug SNR issues with detectors
 - Add tip/tilt control to C&DH system



Acknowledgments

We would like to thank Timothy Crawford, Thomas Cunningham, David Foor, Bruce Hancock, Matthew Heverly, Shannon Jackson, Jess Landeros, Thomas Lee, Bijan Nemati, Thomas Pongetti, Suresh Seshadri, and Chris Wrigley for their considerable technical assistance.

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